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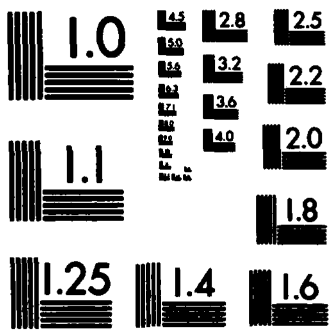


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## ABSTRACT

The Department of Ocean Engineering at M.I.T. has been involved with the production of a robot submarine since the Summer of 1975. A first generation submarine was built, ~~and~~ tested, and ~~it~~ was used for two years before a second generation design was begun. The second generation design was considerably more ambitious than the first, but the design was essentially finished by the Spring of 1979.

~~The~~ development work for the submarine and the production of actual hardware was begun in the Summer of 1979 and was pursued by two separate paths - the electronic systems and the mechanical systems. This thesis describes the mechanical systems development.

# MECHANICAL SYSTEMS DEVELOPMENT AND INTEGRATION FOR A SECOND GENERATION ROBOT SUBMARINE

by

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Lieutenant, United States Navy

B.S., University of Oklahoma
(1972)

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May 1980



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May 1980

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Thesis Supervisor

Accepted by ..........................................
Mechanical Engineering Department
Committee on Graduate Studies

Accepted by ..........................................
Chairman, Departmental Graduate Committee

MECHANICAL SYSTEMS DEVELOPMENT AND INTEGRATION
FOR A SECOND GENERATION
ROBOT SUBMARINE

by

James William White

Submitted to the Department of Ocean Engineering on May 9, 1980, in partial fulfillment of the requirements for the degree of Ocean Engineer and to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

## ABSTRACT

The Department of Ocean Engineering at M.I.T. has been involved with the production of a robot submarine since the Summer of 1975. A first generation submarine was built and tested. It was used for two years before a second generation design was begun. The second generation design was considerably more ambitious than the first, but the design was essentially finished by the Spring of 1979.

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Thesis Supervisor: A. Douglas Carmichael
Title: Professor of Power Engineering

## ACKNOWLEDGEMENTS

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# CHAPTER 1

# INTRODUCTION

As the name of this thesis implies, there has been a great deal of effort, beginning several years ago, toward the development of a Robot Submarine at MIT. This second generation submarine is the culmination at the efforts of very many students and faculty members at MIT and their work should be given appropriate credit. The primary emphasis in this thesis, however, is the final development, construction, assembly, and evaluation of the mechanical subsystems of the second generation robot submarine, ROBOT II.

## 1.1 HISTORY

The first generation robot submarine was built by ocean engineering students during the summers of 1973 and 1974. It was eight feet long, 15 inches in diameter and weighed 250 pounds. It was powered by a one-tenth horsepower motor using a 12 volt lead acid battery as its energy source, and its design speed was three knots. It contained an autopilot, mini-computer, and navigation magnetic compass. The submarine was used successfully to measure water temperatures as a function of depth and it was capable of charting the ocean bottom using an on board sonar system.

## 1.2 ROBOT II DESIGN

Reference (2) gives the preliminary design for Robot II and Reference (1) provides the detailed design of the mechanical systems and hull. Since Robot II is intended to be a free swimmer with an extended mission range, the shape, and thus the drag, of its external hull becomes very important. For that reason, the outer skin of the hull was designed using the 4165 hull form. This is a streamlined shape and contains no parallel middle body. In order to minimize construction difficulties and to provide for easy access, the outer hull is designed using an aluminum frame covered with a fabric reinforced rubber skin. The skin is zippered longitudinally and can be removed easily.

The pressure hull (see Figure 1-1) is composed of six independent compartments fabricated from 6061 aluminum alloy pipe. Except for the compartments at each end, the pressure hull is eight inches in inside diameter and has a wall thickness of one-fourth inch. The end compartments are necessarily smaller to accommodate the decreasing diameter of the 4165 hull form.

The energy source for the submarine is two gell-cell batteries connected to provide plus or minus twelve volts

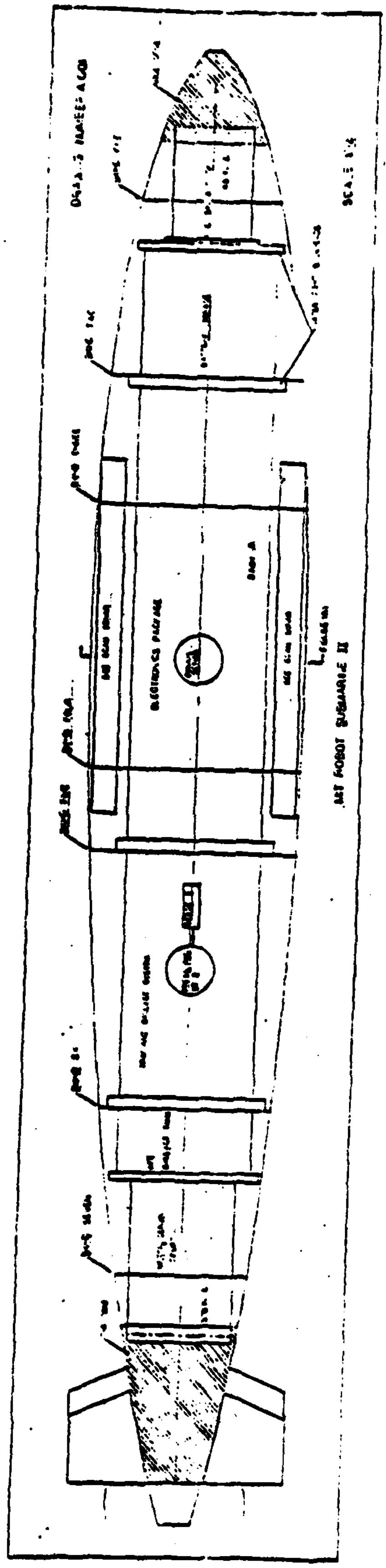


FIGURE 1-1 Robot Submarine
(from Ref. (1))

or twenty-four volts for three hours of operation based upon a predicted power consumption of 60 watts. The batteries were selected in Reference (3) to be compatible with both the propulsion system and the electronics systems on board the submarine. They are inexpensive batteries, but the battery compartment of the submarine is intended to accommodate more energy dense types of batteries which will allow for extended missions of up to fifteen hours.

The propulsion of the submarine is provided by a 24 volt DC motor coupled to a three bladed propeller via a 30.7 to 1 reduction gear. Design speed of the propeller is 273 rpm which gives the submarine a speed of three knots.

The trim and ballasting of the submarine is to be accomplished using ballast tanks provided fore and aft and a system of piping, valves, compressed air and a pump. The system is to be computer controlled and is to account for variations in trim and variations in buoyancy which might result from changes in water temperature or salinity. As designed, it is a fairly complicated system.

Robot II has four control surfaces, two rudders and two dive planes all of the same shape and all located on the extreme after portion of the outer hull. They are two piece controls having one piece fixed to the tail

cone and one movable piece. The movable pieces are mechanically driven by servo motors through a system of shafts and bevel gears.

## 1.3 SUMMARY

As the work for this thesis began, the design of the Robot II submarine was, for the most part, complete. The major components had all been selected and sized. But as in any undertaking of this sort, the final details are often the source of major problems and the development of a well conceived and thought-out idea can only be proved by its accomplishment. That is the intent of this thesis.

# CHAPTER 2

## DEVELOPMENT APPROACH

Once the main design of the Robot II was finalized, the task at hand was to put the finishing touches on the design.

### 2.1 DEVELOPMENT

In many projects of this kind, it is difficult to determine where the design stops and the development begins. Some of the development often begins before the design has been completed and some of the design work is done long after the development is well underway. With Robot II, the situation was somewhat different. Reference (1), which is the design for Robot II, was completed in May 1979. The following summer, the development actually began. While a professional machinist was making the various pieces for the pressure hull, a group of students began the work of checking the final design, fabricating pieces, mounting hardware, and testing. The work was carried out as part of a Ocean Engineering Summer Lab at M.I.T. With the coming of the fall semester, a group of students had to be organized to continue the work independently.

### 2.2 DIVISION OF RESPONSIBILITIES

In order for the development to continue, it was necessary to divide the work into two distinct sections,

the electronic section and the mechanical. The author of this thesis was to be section head of the mechanical portions of the work, and another graduate student was to be section head of the electronics portions. Figure 2-1 is a line diagram of the organization which was established. The areas of responsibility for the mechanical section were to be the outer hull and pressure vessel, the propulsion system, the control fins and linkage, the ballast system, batteries, and all wiring external to the electronics compartment. The electronics section was to be responsible for the computer, compass, sensors, autopilot and sonar systems. The intention was that a different student would be given responsibility for the development of each of the separate items. For the most part that was the case.

As the development of the submarine became more detailed, the communications between the electronic and mechanical section heads was very important. The control fin servo motors, for example, were within the preview of the mechanical section head, but they are controlled by a signal from the electronics. So the selection of wire size, and number of wires required became a cooperative effort. The mounting of the electronics

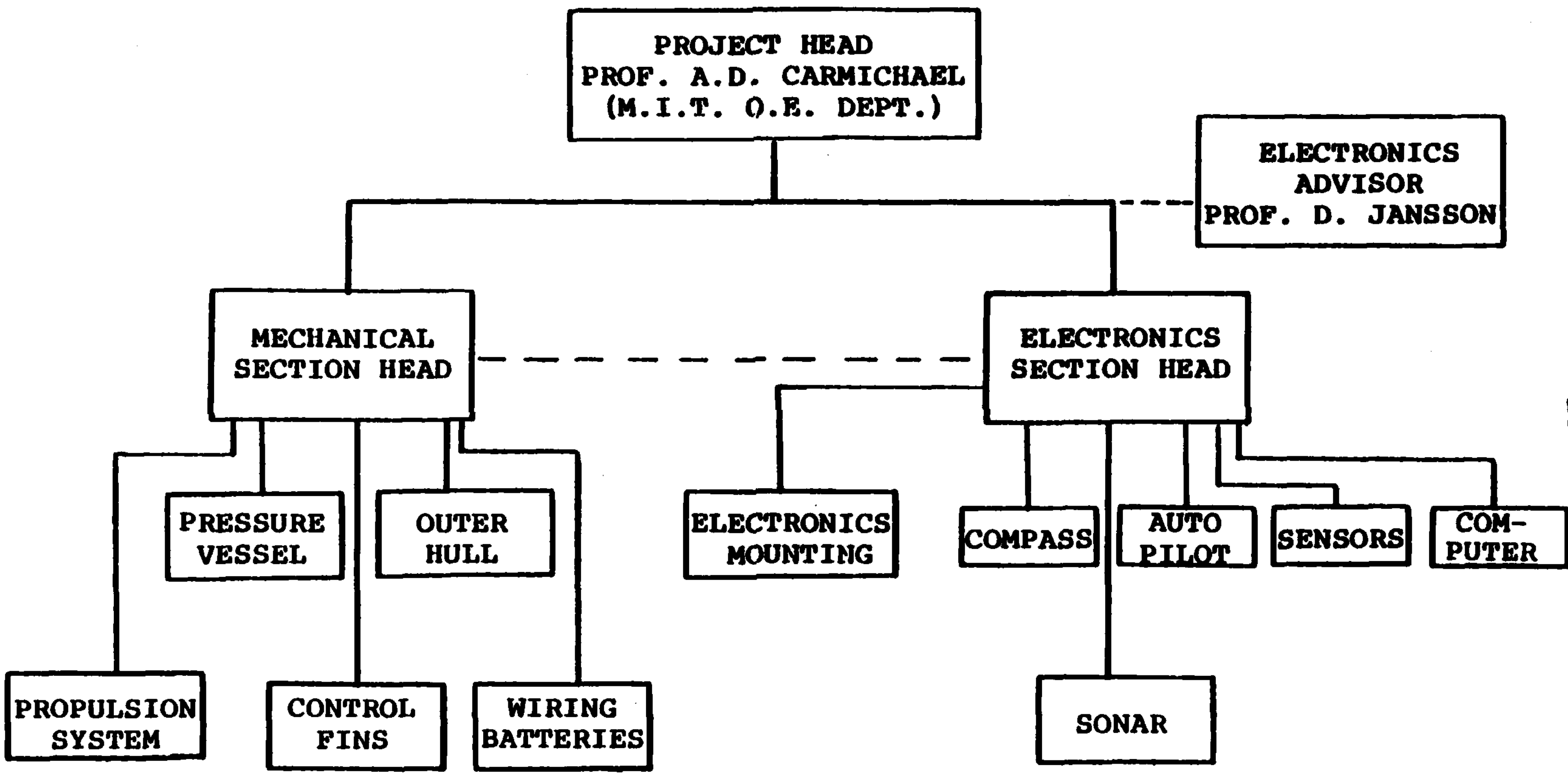



FIGURE 2-1 Organization

equipment within the electronics compartment was a mechanical function but could not be accomplished without input concerning the nature of the electronics. The student who actually built the electronics mounts, therefore, had guidance from both section heads.

## 2.3. Schedule

Although no firm completion date was ever imposed, the New England weather dictated that sea trials would be conducted during the early spring. April 22, 1980 was selected as the tentative sea trial date. In order to meet that schedule, it was necessary to have most of the mechanical portions of the submarine completed by the middle of December, 1979. It was hoped that all electronics could be installed by mid-March 1980 and that system testing continue until the sea trial data.

# CHAPTER 3

# DESIGN CHANGES

Reference (1) gives a fairly detailed design of Robot II. But, as was inevitable, that design required certain changes either because the design could not be accomplished physically or because given more time and being closer to the finished product, the developers of the submarine were able to see a better way of doing things.

## 3.1 THE BALLAST SYSTEM

Since the ballast system as originally designed was very complicated, it was, from the beginning, a likely candidate for design revision. It has, in fact, been one of the most troublesome portions of the Robot II development. Figure 3-1 is a schematic of the trim and ballast system as originally proposed. The pump and motor are bi-directional and the solenoid valves are closed when deenergized. Both pump and valves are computer controlled and work to change trim and buoyancy by adding or removing water from the appropriate ballast tanks. For example, to cause the submarine to become heavy aft, open valve two and energize the pump with a polarity which would cause the pump to remove water from the

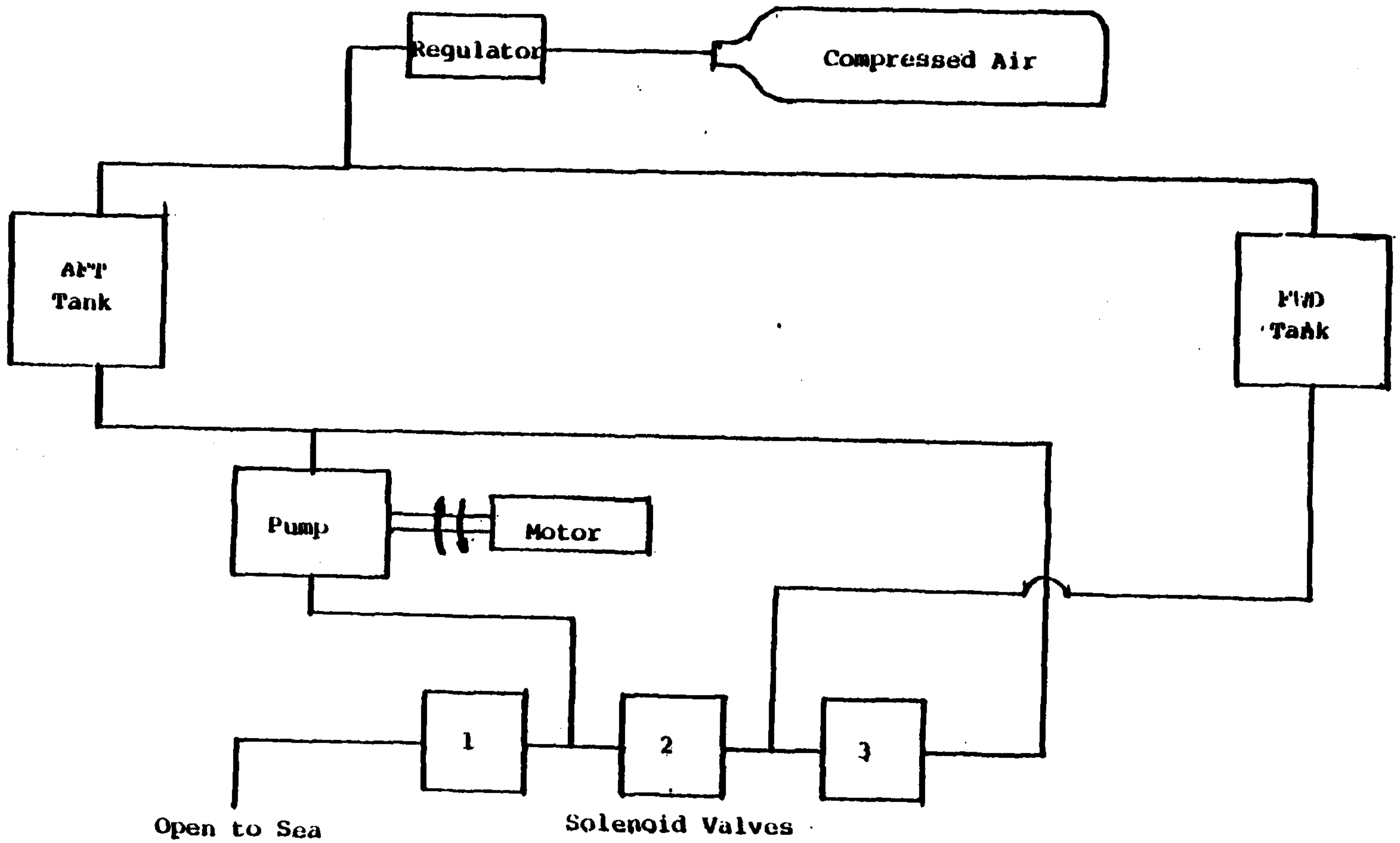



FIGURE 3-1 Original Trim/Ballast System

forward ballast tank and put it into the after tank. To cause the submarine to become heavy forward, energize the pump with reverse polarity. To add or subtract buoyancy open valves one and three and energize the pump with the appropriate polarity. The system is sound as designed except that it is very complicated, draws excessive power, and has no fail-safe provision. The complexity of the system becomes more obvious if one realizes that the air bottle, pump, and valves in Figure 3-1 must be located inside the pressure hull, whereas the regulator, and ballast tank piping connections must be located outside. The number of hull penetrations becomes large and since no radial penetrations are allowed, all penetrations must be made at either the forward bulkhead of the forward ballast tank or the after bulkhead of the after ballast tank. Most penetrations which come through the after bulkhead of the after ballast tank must also go through the forward bulkhead of that tank in order to enter the ballast and trim compartment. This often results in the necessity for more piping than would be otherwise required and since the hull penetrations must be water-tight, the number and variety of fittings required to do the job becomes quite large. Then there is the fact that once the submarine is initially trimed and

launched, there is really nothing which could change that trim. And, in fact, a change in buoyancy is fairly unlikely except at the mouth of rivers or in major current changes. So the neccesity for an on board computer controlled trim and ballast system becomes questionable.

The pump motor which would be used is the same size as the main propulsion motor and uses about fifty watts of power. The solenoid valves use nine watts of power each. So each time the trim and ballast system is required, the power consumption of the submarine is doubled.

A desirable feature of the ballast system would be that it automatically provide positive buoyancy to the submarine in case all electrical power is lost. This system can not de-ballast without electrical power to the pump and solinoid valves. If a malfunction such as a short circuit or broken connection occurred when the submarine happened to be in a negative buoyancy condition, it would have no hope for surfacing and would probably be lost.

The system shown in Figure 3-2 is an attempt to improve the ballast system and to remove the difficulties enumerated above. In this scheme, the requirement for on

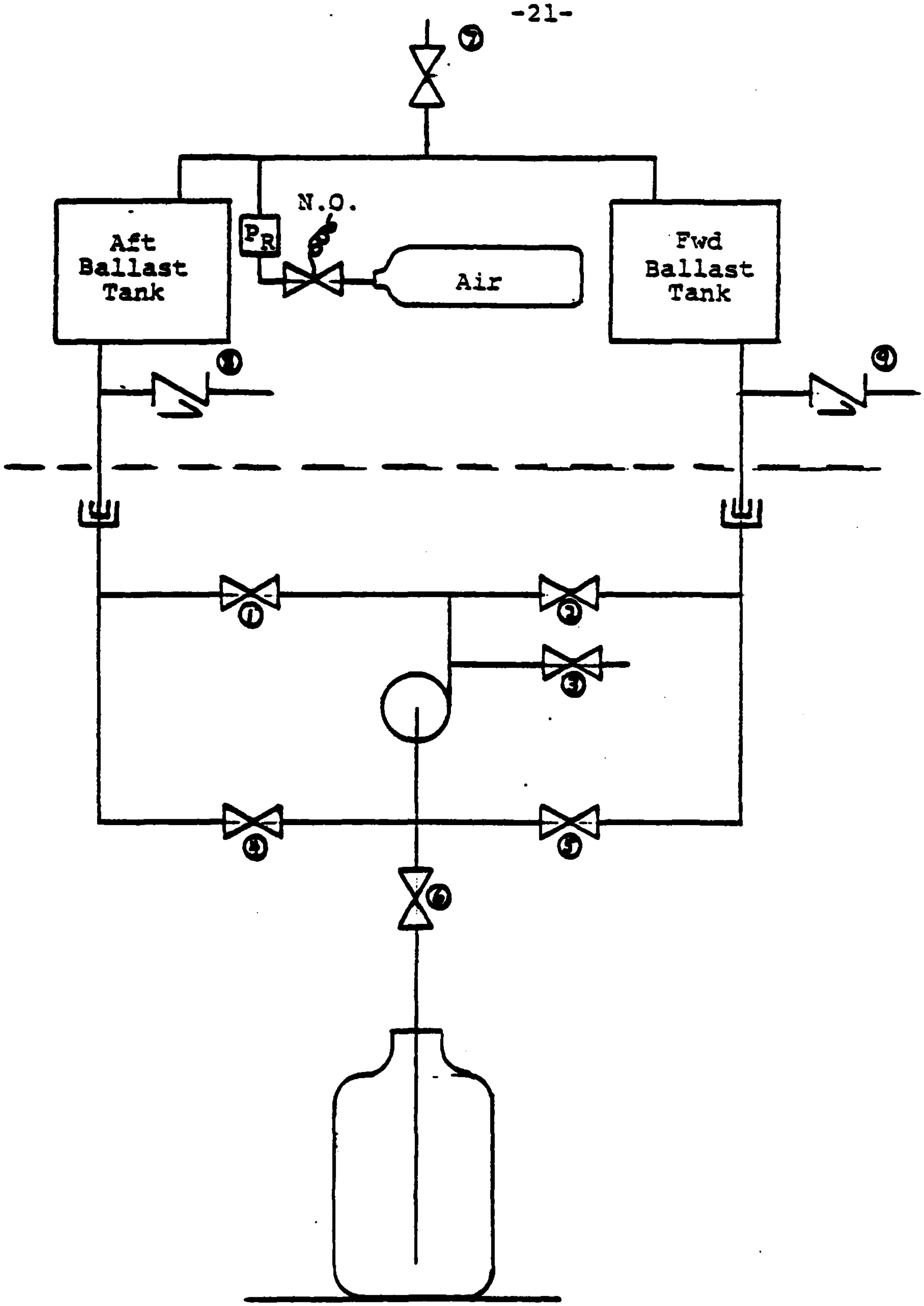



FIGURE 3-2  Improved Trim/Ballast System

board, automatic trim and ballast has been removed. Instead, the system is intended to be used to trim and ballast the submarine prior to each launch. For example, once the submarine has been placed in the water, if it is trimmed down by the stern, an operator would open valves four and two. With all other valves closed, and with the pump running, water would be transferred from the after ballast tank to the forward. If the submarine needed more ballast to submerge, valves six, seven, one and two would be opened. To deballast, valves four, seven, five and three would be opened.

The air bottle and first stage of the pressure regulator have been retained on board, but the three normally closed solinoid valves have been removed as has the pump and motor. A normally open solenoid valve, two quick disconnects and a manual vent valve have been added. This system minimizes hull penetrations and complexity. It also provides a fail-safe feature because if electrical power were lost, the deenergized solenoid valve would open and air regulated to 145 psi above ambient would displace water in the ballast tanks through check valves eight and nine. Valve seven would be left in the closed position except for initial ballasting and deballasting.

Unfortunately, this system does not entirely eliminate the problem of high power consumption. The solenoid valve must be constantly energized to prevent it from opening and it must be able to handle the full pressure of the air bottle, some 2200 psi. The developers were unable to find a valve with high pressure capacity having low power requirements. The valve which most closely met the requirements still consumed nine watts of continuous power and it was very expensive. To move the valve functionally to the down stream side of the pressure regulator would require two more hull penetrations but would reduce the pressure requirement to 150 psi. But even valves at this pressure were found to be large power consumers.

Figure 3-3 is a piping diagram of the system as finally configured. In this system, the air in the ballast tanks is regulated to five psi above ambient. When the solenoid valve is energized, it opens to allow water to be forced out of the tanks. The advantage of this system is that it uses a solenoid valve which requires only a five psi capacity. This valve is very much smaller than the valves for 150 psi capacity. The valve is normally closed so it only requires power when it is

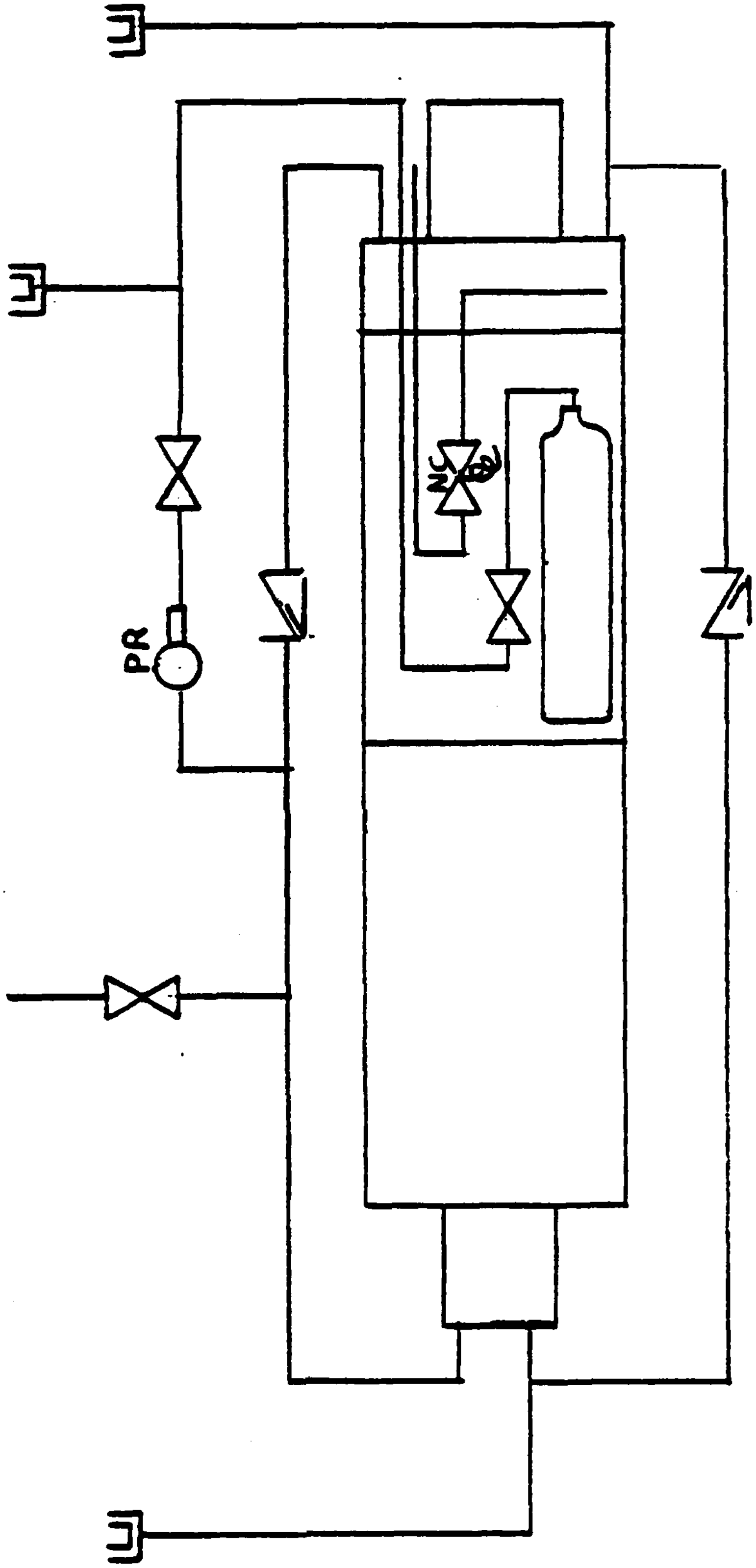



FIGURE 3-3  Final Ballast System Configuration

being used. In order to provide a fail safe feature, extra electrical equipment had to be added. Figure 3-4 is a schematic of the fail safe system. When normal electrical power is lost, relay R1 is deenergized causing the solenoid valve to be energized from a 12 volt dry cell battery which is mounted next to the solenoid. The 12 volt dry cell is considered to be emergency power.

## 3.2 BEVEL GEAR SUPPORTS

One of the problems with the original design which was corrected early in the development concerned the stability of the two inch bevel gear shown in Figure 3-5 (from Reference 1). It is to be noted that the shaft of this gear has support at only one end. The original design assumed that the shaft bearing would be deep enough to support any moment that the gear and shaft may have applied to them. It was recognized, however, that the slightest amount of wear in either bearing, shaft, or gear could cause the teeth of the gear to disengage. In order to improve the reliability of the control system, an extra bearing support was added to correct the problem as shown in Figure 3-6. A related problem is that the original design called for a hexagonal spline between the bevel gear shaft and the control fin

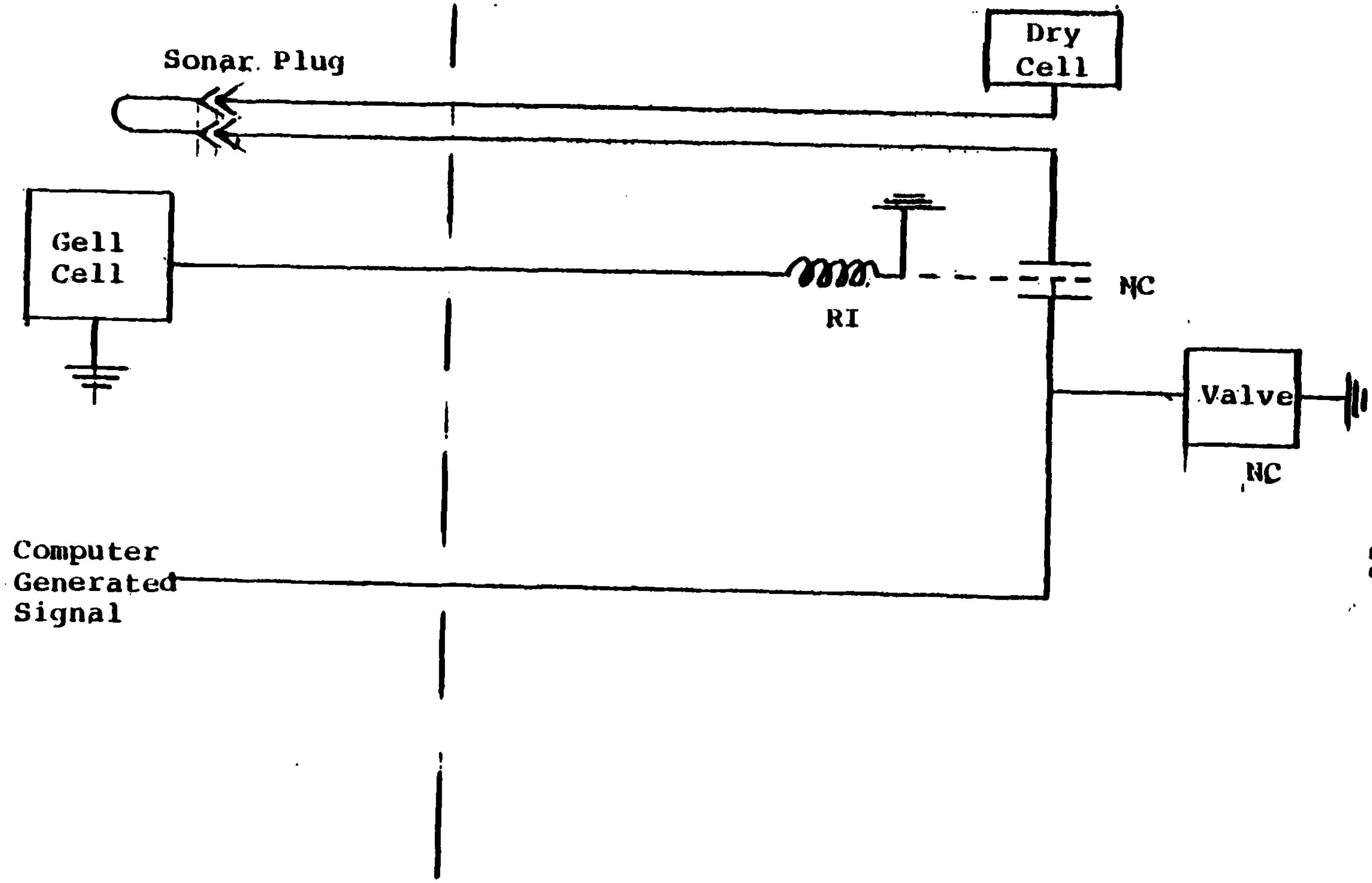



FIGURE 3-4 Ballast Fail-Safe System

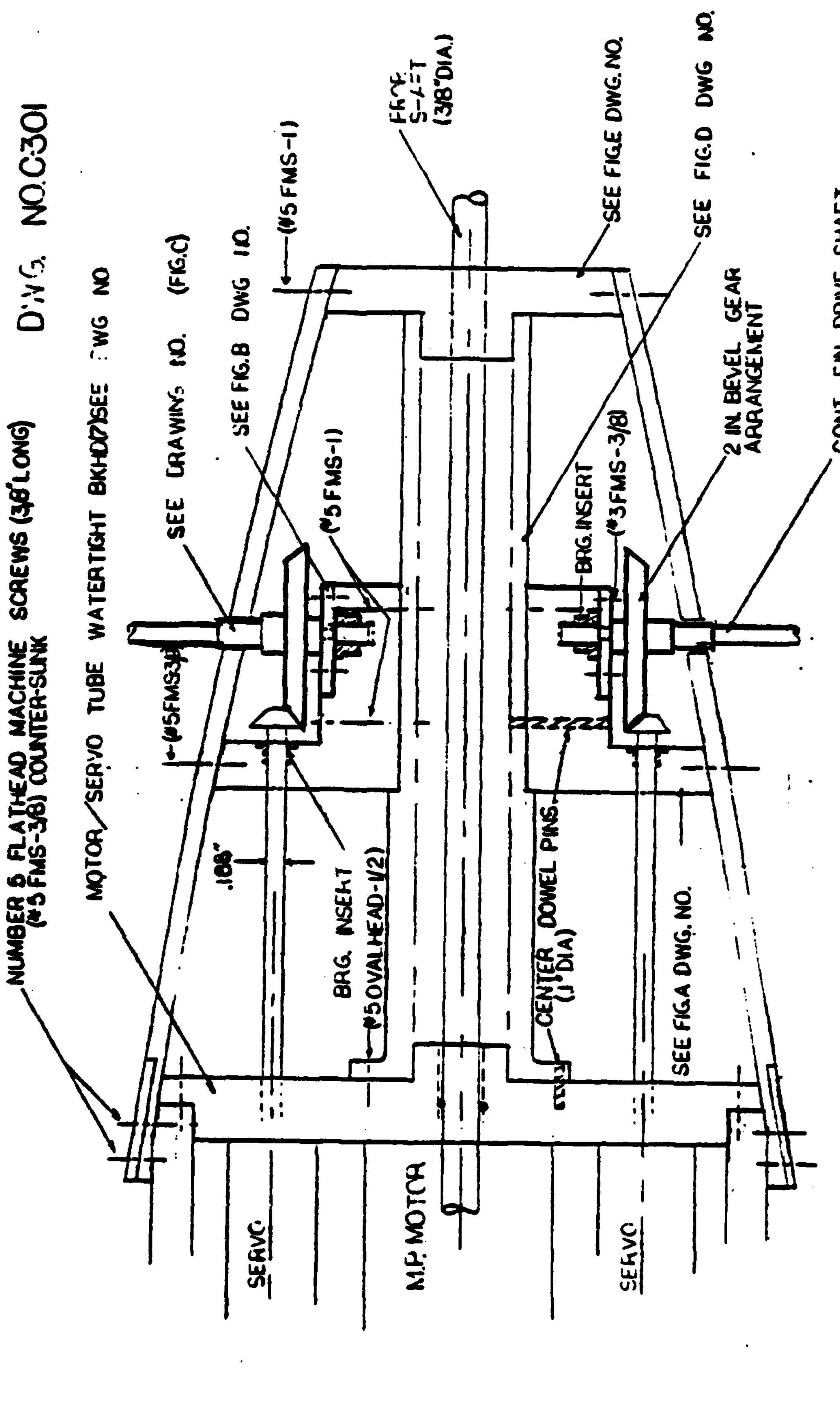



FIGURE 3-5 CONTROL SYSTEM LINKAGE

FULL SCALE

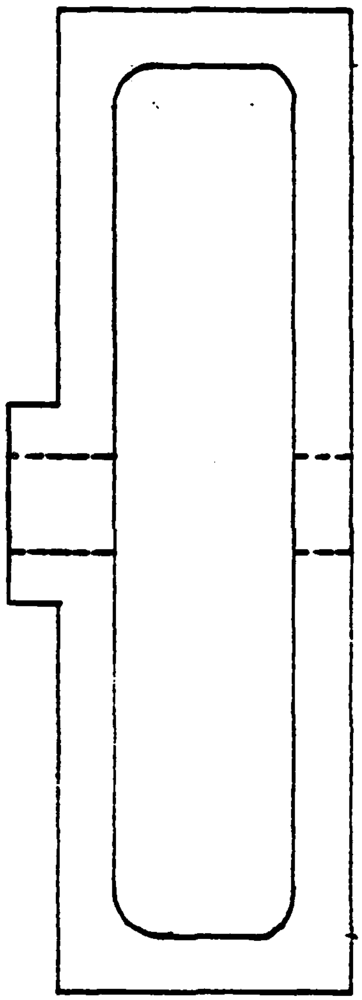


FIGURE 3-6 Bearing Support

shaft. This spline originally had too much backlash and was replaced by a sleeve and set screw connection.

### 3.3 RUBBER SKIN TERMINATIONS

One of the more novel concepts of the design of Robot II is that of using a rubber skin as the outer hull form. And since it is novel, one would expect the implementation of the idea to have some difficulties. One of the most serious of the problems to be solved was that of the termination of the rubber at the nose and tail cone sections. It was originally planned (see Figure 3-7-A) that the rubber skin should be folded around a non-elastic braided belt and that the belt would be sized to fit snuggly against the nose and tail cones. It was found, however, that the braided belts were difficult to attach to the rubber and to the zipper and that once attached, they cause a knuckle in the otherwise smooth and streamlined shape of the rubber skin. Tow tank tests without the braided belts, however, showed that the skin had too much leakage and could not be completely inflated by the stagnation pressure at its nose as originally intended. Since the shape was not well inflated, it did not streamline well and the drag was therefore increased. The solution to the problem was to use elastic rubber, circular bands at the skin terminations as

shown in Figure 3-7-B. These elastic bands (actually cut from an automobile tire inner tube) reduced the drag on the submarine considerably.

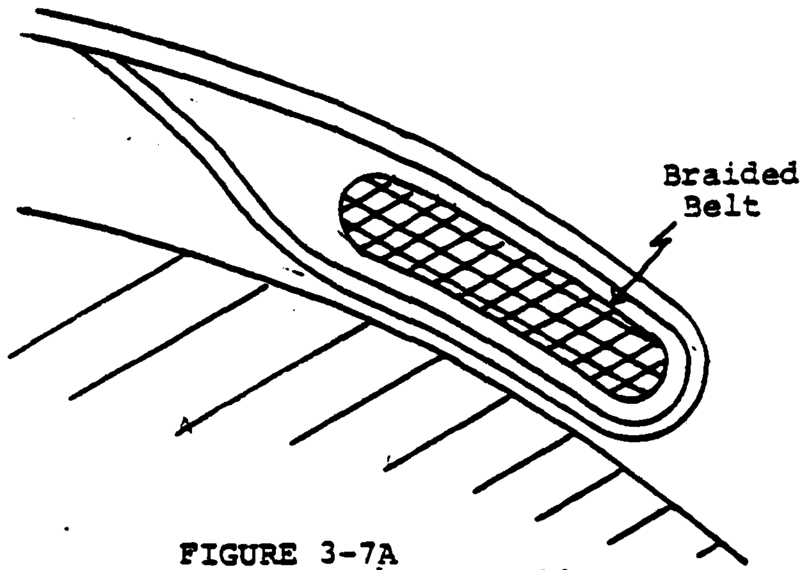



FIGURE 3-7A

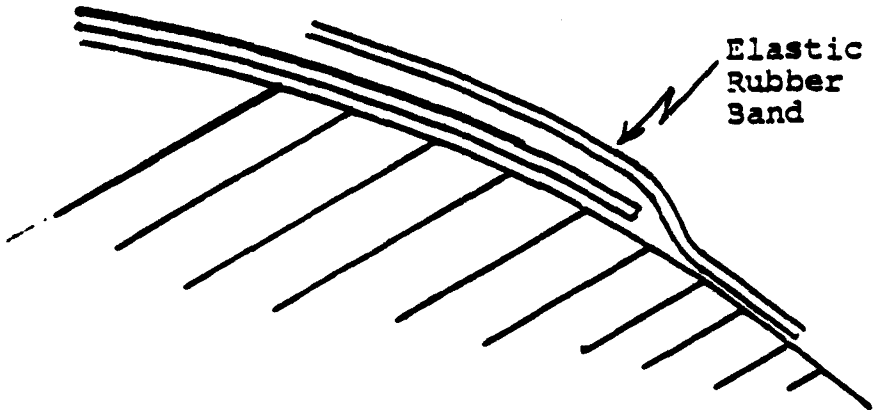



FIGURE 3-7B

Rubber Skin Terminations

# CHAPTER 4

# DETAILED DESCRIPTION

Robot II is more than a student project. It is intended to be used in the future for various scientific endeavors. As such, there will be times when the submarine must be disassembled for maintenance. This chapter is intended to be used as a guide to assist in maintenance. A description of each major section will be given as well as some suggestions for more efficient procedures.

## 4.1 PRESSURE HULL AND INTERNAL DETAILS

The pressure hull is a series of cylinders machined from 6061 aluminum alloy piping (see Figure 1-1). Each separate cylinder is one functional compartment within the submarine. The compartments are from fore to aft: the forward ballast tank, the battery compartment, the electronics compartment, the trim and ballast compartment, the after ballast tank, and the motor tube. The motor tube has an inside diameter of six inches; the forward ballast tank inside diameter is five inches. All other compartments have an eight inch inside diameter. The wall thickness of each compartment is one-fourth inch. At the end of each large compartment is a flange. The flanges mate with

bulkheads which were machined from three-fourths inch aluminum alloy plate. The flanges are grooved to accommodate O-ring seals. Reference (1) contains a complete set of dimensioned drawings of the bulkheads and flanges. The bulkheads are numbered one through seven from fore to aft. Except for bulkhead number one which is epoxied in place, the bulkheads are bolted to the flanged cylinders. Care must be taken when tightening or removing these bolts so that the bulkheads do not become misaligned inside the cylinder flanges, and so that undue compressive stress is not placed on the O-ring seals.

#### 4.1.1 Battery Supports

In the future, Robot II will be powered by a much longer-lived battery than is currently installed. The battery compartment must, therefore, remain capable of housing any shape or configuration of batteries which might prove feasible. This feature of the battery compartment eliminated the possibility of any permanent support fixtures and led the developers to the choice of supports shown in Figure 4-1. Here, the batteries actually rest at their corners on the cylinder of the battery compartment. A plate of one-eight in. aluminum

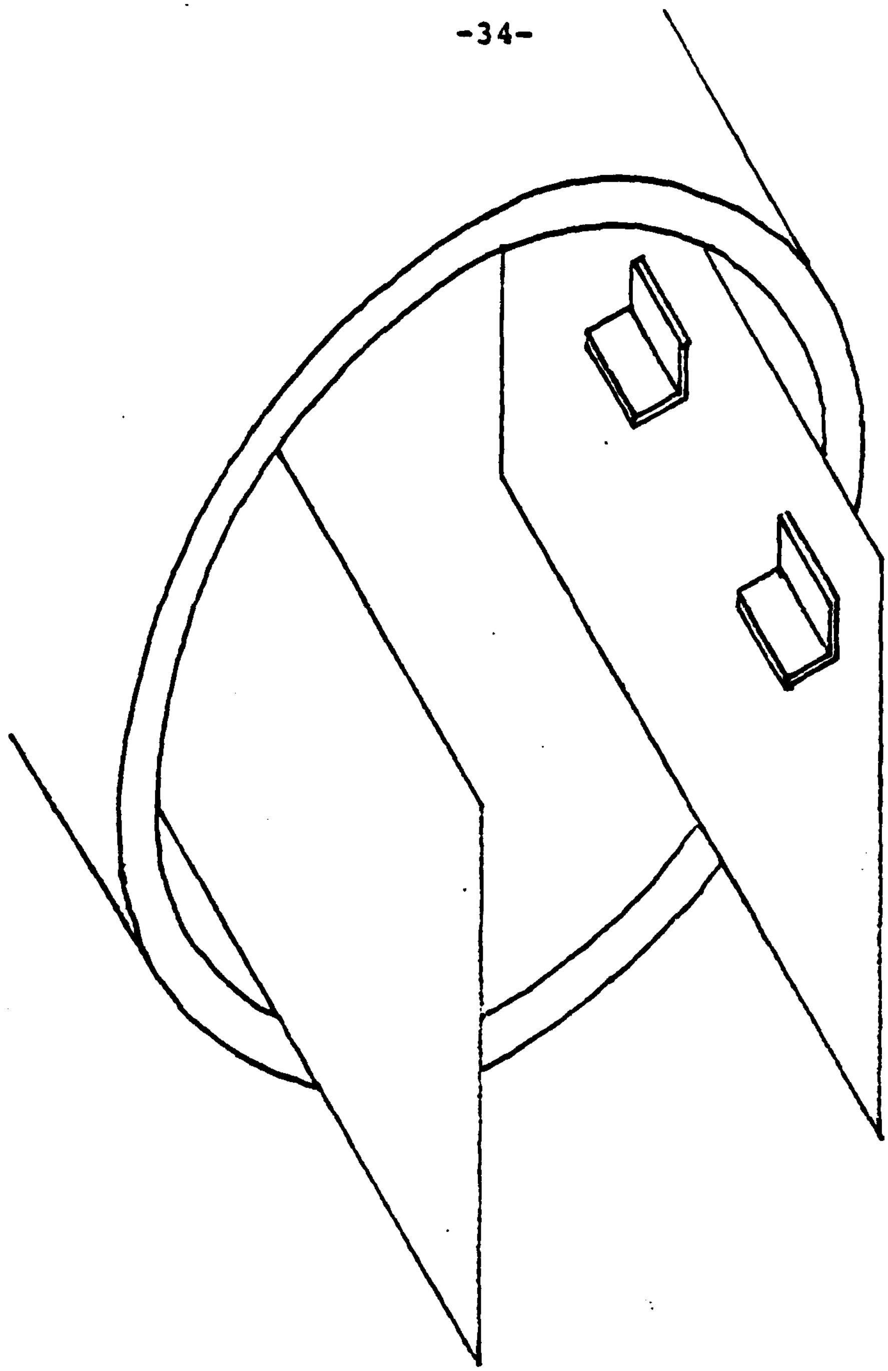


FIGURE 4-1 Battery Supports

is placed outboard of each side of the batteries to prevent their motion athwartships. Vertical motion is prevented by pieces of one half inch aluminum angle which are attached to the plates. Longitudinal motion is prevented by the end bulkheads of the battery compartment. The plates are cut with very close tolerances so that the friction between the edges of the plates and the cylinder wall prevents the rotation of the batteries. When the batteries are installed in this configuration, their center of gravity is below the center of the submarine. This greatly enhances the stability of the submarine since the batteries are one of the heaviest items on board. Also, there is sufficient room above the batteries to allow for the passage of wires and cables. Note should be taken of the fact that the angle aluminum on the starboard side of the compartment is slightly smaller than that on the port side. The reduced size allows for the passage of the terminal clips when the batteries are removed. This arrangement should never be reversed. That is, <u>the battery post terminals must always remain on the starboard side</u>! To change the arrangement could reverse the polarity of the entire electrical system and cause a great deal of damage.

### 4.1.2 Electronics Support

The electronics compartment of Robot II is by far the largest single space. Its arrangement, therefore, was somewhat more challenging. Additionally, the progress of the electronic assembly did not coincide well with the progress in the mechanical sections and the electronics support system had to incorporate a great deal of flexibility. The major portion of the electronics is on ten circuit cards which are supported in a commercially purchased circuit card rack. The length of the rack is approximately half that of the whole compartment. Besides the card rack, the electronics compartment must also house the magnetic compass, pitch and roll sensors, and tape recorder. Since the compartment is so long, all its contents must be able to slide out of either end of the cylinder. To accomplish the support of the equipment, two pieces of three-fourths by three-fourths inch aluminum angle were attached to the side of the electronics compartment. Figure 4-2 shows an end view of the arrangement. The aluminum angle rails are the length of the compartment so that the card rack can be mounted at either end or in the middle. Other pieces of equipment were mounted

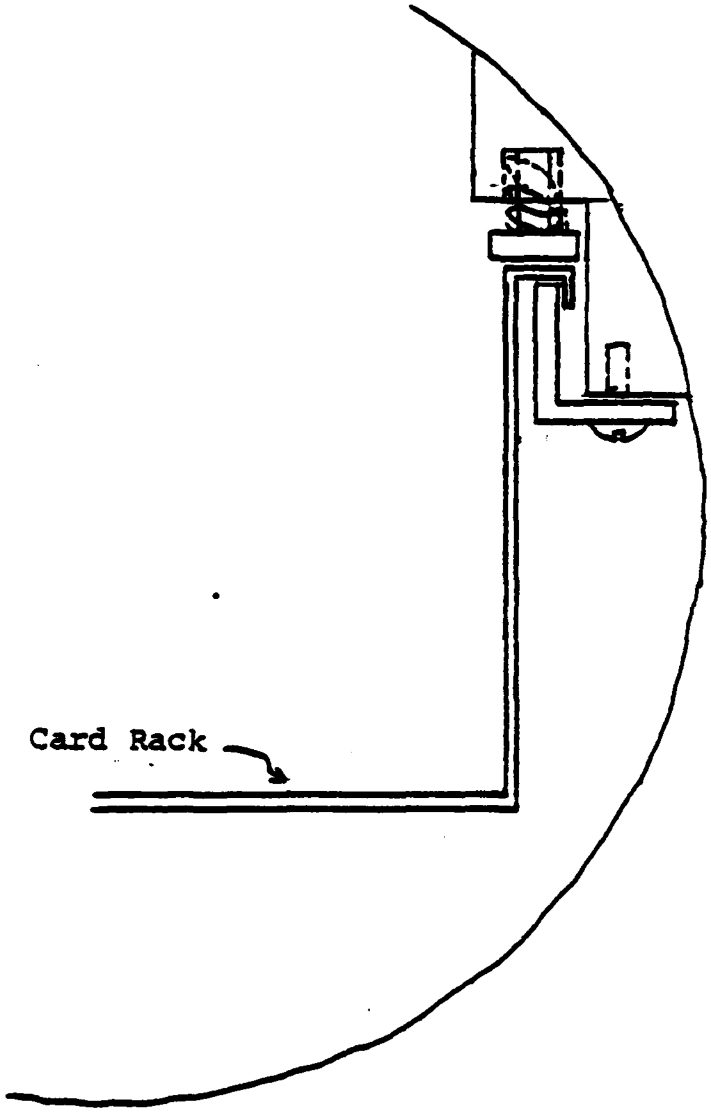



FIGURE 4-2 Electronic Support

by building hooks on them similar to the lips at the top of the circuit card rack. In order to prevent vertical motion of the equipment, a three-eights by one-eight inch aluminum bar was spring mounted above the support rail. The springs were chosen to provide enough friction to prevent longitudinal movement of the equipment but not so much that easy removal is impaired. There is sufficient room below the mounted equipment to allow for the passage of wires and cables.

### 4.1.3 Trim and Ballast Compartment Arrangement

Figure 4-3 shows the arrangement of the trim and ballast compartment. There are some features of the compartment which made it difficult to arrange. First, the air bottle is very heavy so it must be at the lowest possible point within the compartment to add stability to the submarine. Secondly, the equipment within the compartment is mounted in a variety of ways. Some requires horizontal panel mounting; some must be mounted vertically. The compartment contains many piping connections for both air and water, and there is some electrical equipment within the compartment. In order to provide as much mounting space as possible, the developers decided to install a horizontal deck

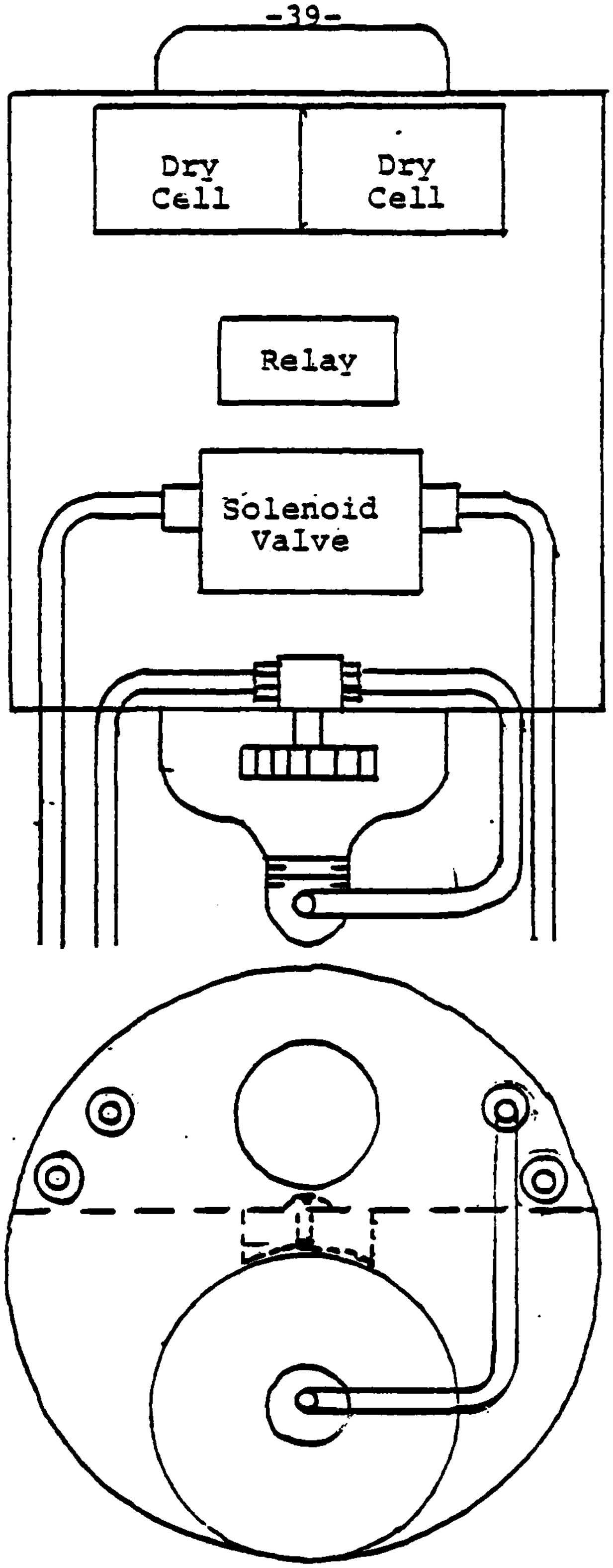



FIGURE 4-3  Trim and Ballast Compartment

between two vertical, non-structural bulkheads. The deck and bulkheads were cut from one-eight inch aluminum plate. The bulkheads are slightly less than eight inches in diameter so that they slide easily inside the cylinder of the compartment. The deck is attached to the bulkheads using one-half by one-half inch angle aluminum brackets and is at the four inch level within the compartment. At the bottom of each bulkhead a hole is cut so that the bulkheads will fit over the air bottle. A manual, high pressure, stainless steel valve is supported by the after mounting bulkhead. This valve is connected to the air bottle through stainless steel one-fourth inch tubing and a special elbow which mates the one-half inch pipe threads of the bottle to the tubing. The other side of the valve is connected to a bulkhead penetration on the after bulkhead of the compartment. The valve serves as isolation between the high pressure air bottle and the rest of the air system. It should be closed before any maintenance is performed on the air system. But it must be open during submarine missions.

There is a solenoid valve mounted on the deck of the compartment. It is the control for the release

of water from the forward and after ballast tanks. The valve is normally computer controlled and opens when the solenoid is energized. In the event of loss of electrical power, the relay mounted forward of the valve is deenergized. The contacts of the relay close to provide electrical connection between the solenoid valve and the dry cell batteries mounted next to the forward non-structural bulkhead of the compartment.

Maintenance in this compartment requires special care. The air bottle will normally be pressurized to 2250 psi. Additionally, there are water lines and electrical connections. So there is a potential to do damage to the submarine or even personal injury. Access to the trim and ballast compartment should always be made at its after end by removing the bolts which secure bulkhead number five and the after ballast tank. Then, with all fittings still connected to bulkhead number five, the entire trim and ballast compartment interior assembly should be withdrawn until the handwheel of the air isolation valve can be reached. <u>The air isolation valve must be closed before any fittings are disconnected inside the trim and ballast compartment</u>. Once the valve is closed, the fittings

at bulkhead number five can be disconnected and the trim and ballast system removed.

If it is necessary to remove the air bottle for any reason it must first be depressurized. The air can be released from the bottle by slowly reopening the air isolation valve a small amount. Do not disconnect the stainless steel tubing between the air bottle and the air isolation valve until the air bottle has been depressurized. The air bottle is held in place by a friction pad and screw (shown dotted in Figure 4-3) which prevents the bottle from rotating or moving longitudinally. The screw must be loosened slightly before the air bottle can be removed. After the air system is reassembled, it should be hydro tested to 3000 psi before it is operated.

#### 4.1.4 After Ballast Tank

All the electrical connections to the submarine's propulsion motor and control devices must pass through the after ballast tank. Since the tank is only two inches long, there is not room for the installation of special water proof connectors, and other arrangements had to be made. The penetration was made by installing one-half inch thermocouple fittings on the

outside of the tank bulkheads through which a piece of nylon tubing was passed. The tubing makes one half turn of a spiral as it passes through the tank to allow for separation of the bulkheads. Fifteen wires were then pulled through the tubing. All the air and water penetrations for the trim and ballast system were made in a similar way. The large number of tubes which pass through the after ballast tank make its assembly somewhat difficult and it should not be disassembled without good reason.

On the starboard side of the after bulkhead of the ballast tank is a three-eights inch stainless steel vent plug. This plug should be removed whenever the air system is being charged or hydro tested. If the plug is not removed, a rupture of the air tube inside the ballast tank would cause a severe pressure buildup and possible explosion of the tank.

#### 4.1.5 Motor Tube

The motor tube contains the propulsion motor and its associated hardware plus the four servo motors for the submarine control surfaces. Special mounts had to be machined for each of the motors to insure proper alignment of the motor shafts. Each

servo-motor mount is an aluminum cylinder which is partially threaded at the inside of its base and has an axial slot along its side. If the servo-motor is to be removed, its shaft must be decoupled by loosening the shaft coupling which can be reached through the slot at the side of the cylinder. A 25 K-ohm feedback potentiometer is affixed to each servo-motor shaft, and must be removed by pulling the shaft through the body of the potentiometer which is held in place by friction alone. To remove the servo-motor mount, loosen the set screw at its base and rotate the assembly counter-clockwise. Once the mount has been removed, the threaded cylinder support can also be removed to gain access to the shaft seal of the control surface shaft. The propulsion motor is similarly mounted except that the base of the mount is flanged rather than threaded. The shaft coupling for the propulsion motor was custom made. Electrical connections are made through a plug which connects to the fifteen wire, ballast tank penetration.

## 4.2 CONTROL FIN LINKAGE

Each control fin servo motor is connected to its rudder or plane by way of three-sixteenth inch shafting and a bevel gear. The bevel gear has a 3.7 to one reduction so the servo-motor must rotate 111 degrees each way from zero in order to cause the control fin to rotate plus or minus thirty degrees. The shafting is precision ground to insure zero leakage at the shaft seal interface. The shaft seals are made of teflon and are reinforced with a garter spring. The shafts are supported by teflon bearing inserts.

## 4.3 Piping

Figure 3-3 is a piping diagram of the trim and ballast system on board Robot II. The piping inside of the trim and ballast system compartment is discussed in paragraph 4.1.3. The high pressure air tubing which passes through the after ballast tank is connected to a tee fitting. One leg of the tee is used to charge the air bottle by way of a quick disconnect. Downstream of the tee fitting is an isolation valve which should be closed to prevent air pressure depletion when the submarine is not being used. The pressure regulator is a two stage scuba regulator

which has been adapted for use on Robot II. It is the only brass part of the submarine and is therefore electrically insulated from its mountings to prevent galvanic corrosion. The regulator and surrounding area must be thoroughly rinsed with fresh water after each mission. Air pressure is reduced to 145 psi above ambient by the first stage of the regulator and reduced again to five psi above ambient by the second stage. Ambient pressure is sea water pressure at submarine depth. The five psi air is piped to the top of both ballast tanks. A vent valve is attached to this pipe to allow the ballast tanks to be filled with water prior to each mission. The vent valve is toggle operated and is positioned in such a way that the zipper of the rubber skin can not be secured if the valve is left open. The bottoms of the ballast tanks are interconnected by three-eights inch tubing. A check valve is installed with a one psi cracking pressure to prevent free flood between the two ballast tanks. Quick disconnect fittings are provided to allow each tank to be filled with water independently so that trim can be adjusted before each launch. Tubing unions have been installed so that the piping

can be removed as a whole when the outer hull is removed.

## 4.4 WIRING

The wiring diagram for Robot II is Figure 4-4 and its legend is Table 4-1. The submarine was wired so that all electrical components in each separate compartment can be disconnected at one plug. The plug at water tight bulkhead number two is specially designed for deep submergence and is the only electrical penetration which must withstand full sea pressure. It is a 22 pin connector. Most of the pins are required for sonar array connections, but several spares were provided to allow for future modifications. Some of the spare connections are to be used to interface between the on board computer and the shore based facility.

The batteries are wired to provide twelve volts above and below a common reference or a total of twenty-four volts, where needed. The common wire is not connected to the hull of the submarine in order to reduce the potential for short circuits in the wiring and to minimize electronic noise and interference.

Bulkhead penetrations into the electronics compartment are made through receptacles on either

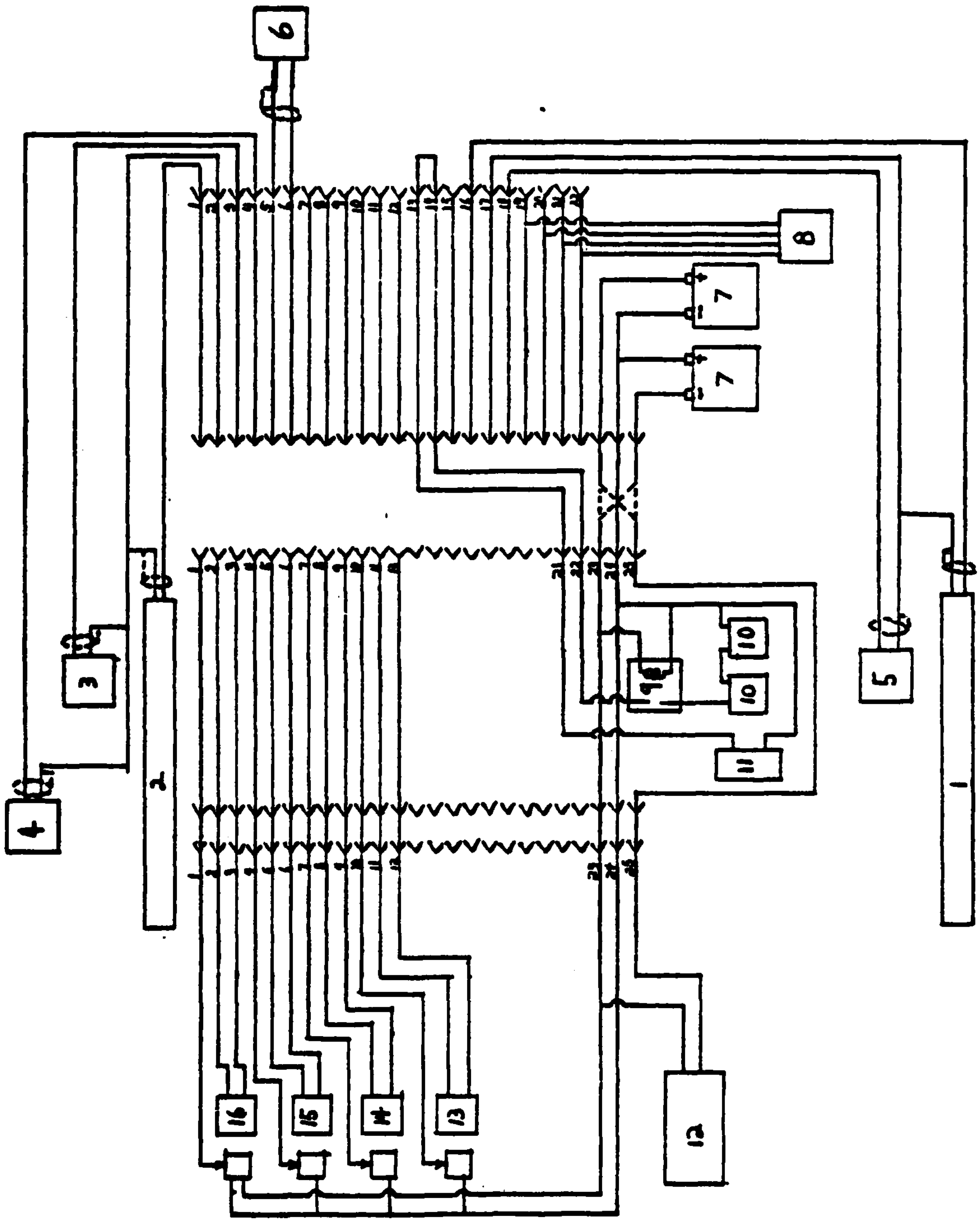


FIGURE 4-4 Wiring Diagram

| | |
|---|---|
| 1 | STBD Side Scan Array |
| 2 | Port Side Scan Array |
| 3 | Communications Sonar |
| 4 | Pinger |
| 5 | Bottom Finding Sonar |
| 6 | Collision Avoidance Sonar |
| 7 | Gel Cell Battery |
| 8 | Depth Sensor |
| 9 | Relay |
| 10 | Dry Cell Battery |
| 11 | Solenoid Valve |
| 12 | Propulsion Motor |
| 13 | STBD Plane Servo Motor |
| 14 | Top Rudder Servo Motor |
| 15 | Port Plane Servo Motor |
| 16 | Bottom Rudder Servo Motor |

TABLE 4-1 Wiring Diagram Legend

side of the bulkhead which have been wired together through a rectangular hole. These are not water tight connections but the rectangular holes have been filled with wax to prevent leakage of hydrogen gas which might be produced in the battery compartment. The plugs in the motor tube and the after plugs in the trim and ballast system compartment are not bulkhead mounted because of the way in which the wiring passes through the after ballast tank.

## 4.5 EXTERNAL FRAME AND RUBBER SKIN

The design of Robot II provides for a framework to support the rubber skin when it is not being inflated by the dynamic pressure of the submarine. Reference (1) contains drawings of the pieces of this external support fixture. The various pieces are put together with aluminum machine screws and once assembled, they provide for support of all the equipment which is mounted external to the pressure hull. All the sonar transducers, the pressure regulator, all external piping, and the lifting eye bolts are held in place by the external framework. The nose and tail cones are attached to the framework and the rubber skin is placed over it and zipped. The rubber

skin itself is made in four pieces which were sewed together by a professional sailmaker and then readjusted to fit the framework as closely as possible.

# CHAPTER 5

## TESTS AND EVALUATIONS

In order to enhance the probability of successful sea trials, various tests were performed during the development of the various parts of Robot II.

### 5.1 VACUUM TEST

To prove the concept of the o-ring seals between the compartments of the submarine, a vacuum test of the assembled hull was performed. In order to test the compartments individually, a procedure was developed which would check each bulkhead after it was totally assembled. Small holes (.06 inch) were drilled through water tight bulkheads number two, three, five and six. The holes were then enlarged part way through and tapped to accept a 10-32 screw and o-ring. A special fitting was manufactured to permit the attachment of a vacuum hose to the small holes in the bulkheads. Using a small vacuum pump, a vacuum of 60 cm Hg was maintained in each compartment for thirty minutes.

The vacuum test was completed before any penetrations had been made in the bulkheads for wires or piping runs so the o-ring seals were tested alone. The vacuum tests

were totally successful except that the motor tube could not be tested at that stage of development because the propulsion and servo motor shaft seals had not yet been installed.

Once finally assembled, the entire pressure hull, except for the ballast tanks, can be vacuum tested by using only the one vacuum plug which was installed on the forward side of watertight bulkhead number two. This is possible because the wire and piping runs which were installed, have broken the integrity of the internal bulkheads and allows free communication of air among the compartments. Since the flow of air between some adjacent compartments is small, however, the vacuum pump will take at least ten minutes to bring the vacuum within the entire hull to 60 cm Hg. Once the vacuum has reached that value, the vacuum pump should be secured and isolated and the vacuum maintained for an additional fifteen minutes. A vacuum test should be performed whenever the water tight integrity of the pressure hull is suspect.

## 5.2 TOW TEST

As recommended by Reference (1) the resistance of the outer hull form was tested in the M.I.T. Towing Tank. Instead of towing the entire submarine, only the outer

hull framework and rubber skin were tested since they define the shape and thus the drag of the hull.

The outer hull was attached to the apparatus shown in Figure 5-1 which was supported by the M.I.T. Towing Tank carriage. Measurements were made at half knot speed intervals at speeds up to three knots. Since the drag of the towing apparatus had to be subtracted from the total in order to determine the submarine drag, the apparatus alone was towed at the same speed increments. The results are shown in Table 5-1.

The model test performed in the M.I.T. Propeller Tunnel and described in Reference (1) predict a drag at three knots of 2.574 pounds. This drag was calculated by multiplying the results of the model tests by a margin factor of 1.25. The model prediction alone then is 2.06 pounds. The drag predicted by the calculations in Appendix I predict a drag of 2.17 pounds which is only five percent higher than the model predictions. The first two tank results did not correlate well, however, with predicted values. The towing tank measurements showed that the drag of the submarine would be 4.78 pounds. Several possible reasons for the increased resistance were proposed. It was thought that the rubber

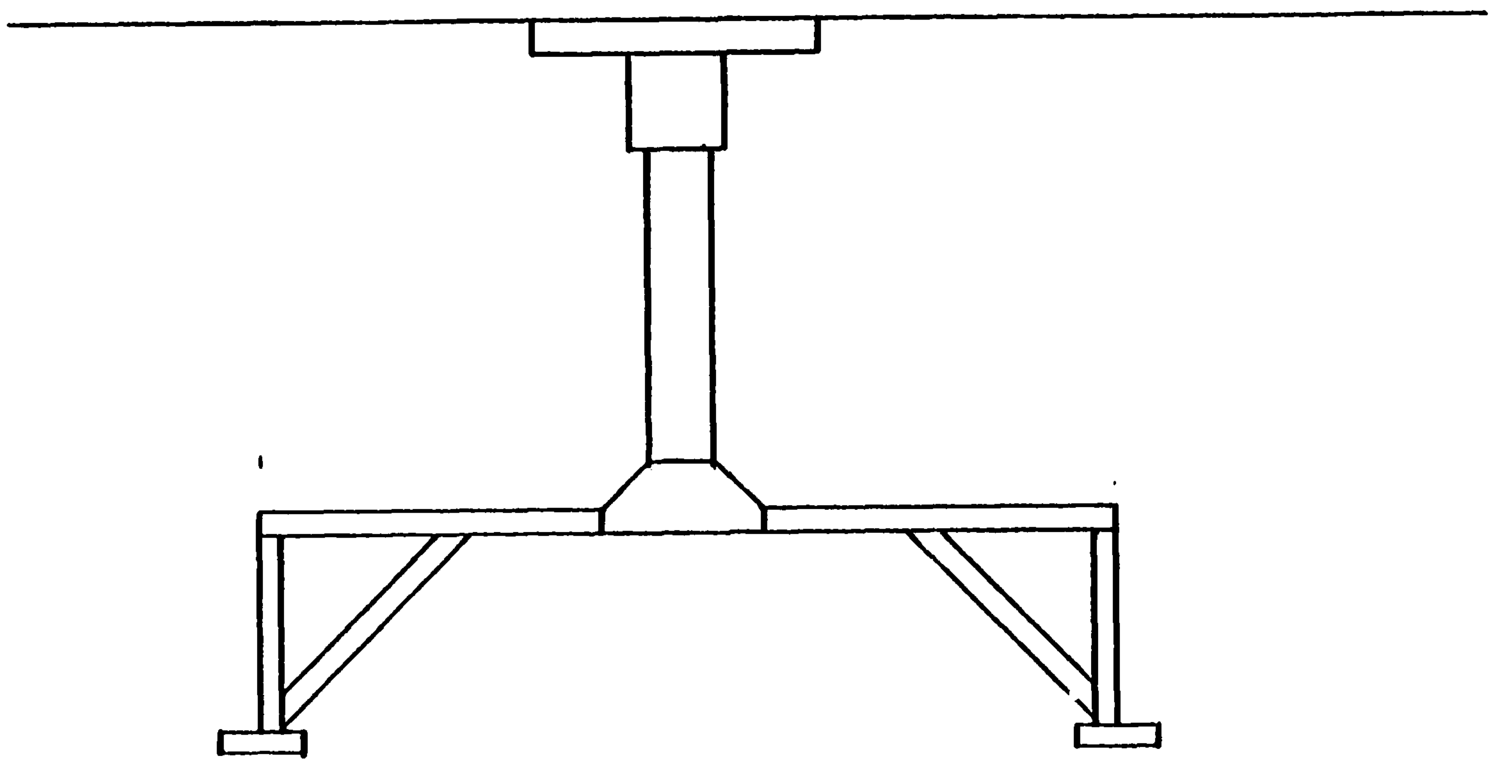


FIGURE 5-1  Tow Test Appartus

| Speed KTS | Total Drag lbs | Support Only | Sub Only |
|---|---|---|---|
| 0.5 | 0.271 | 0.095 | 0.176 |
| 1.0 | 0.976 | 0.397 | 0.579 |
| 1.5 | 2.195 | 0.887 | 1.308 |
| 2.0 | 3.834 | 1.534 | 2.300 |
| 2.5 | 5.950 | 2.350 | 3.600 |
| 2.733 | 6.250 | 2.590 | 3.660 |
| 3.021 | 7.913 | 3.125 | 4.788 |

TABLE 5-1

Results of First Towing Tank Test

skin terminations did not adequately seal the ends of the skin and so the submarine did not fully inflate. Also, the ends did not mate well with the nose and tail cones and so there was extra drag produced. There was the possibility that the submarine was not at exactly zero angle of attack and so an induced drag was added. But most probably, the problem was in the method by which the drag of the submarine was measured. The force block used to measure the drag of a model in the M.I.T. Towing Tank is shown schematically in Figure 5-2. The block consists of two flat plates which are separated by four precisely machined aluminum posts. The posts are designed so that the shear displacement of the two flat plates is proportional to the drag force of the model. The relative displacement of the two plates is then measured by the load cell in the center of the block. Normally, the block is placed directly on the model and is connected to the towing carriage by a long arm. But the load cell in the force block is not waterproof, and the submarine had to be tested while submerged. The force block was therefore mounted directly to the carriage and the towing apparatus was suspended from it. Thus the centerline of the submarine was located

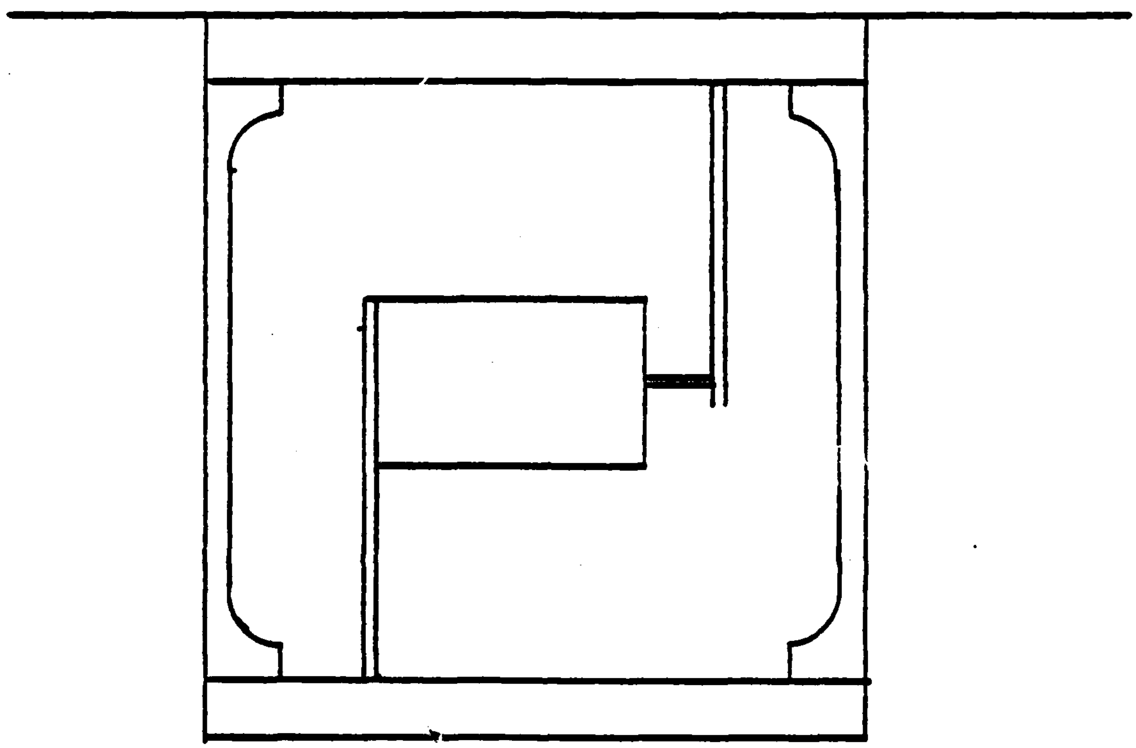


FIGURE 5-2 Tow Tank Force Block

thirty-two inches below the force block. The moment produced by this long arm was sufficient to cause the force block to be displaced and to add considerably to the measured value of drag.

The second time the submarine was tested, the new skin terminations were added to reduce leakage and the towing apparatus was modified to eliminate the effects of the long moment arm. Instead of bolting the apparatus directly to the force block, a hinge was attached between the two and the submarine was held at zero angle of attack by ropes which were tied to the ends of the towing apparatus and to the carriage. Since the ropes penetrated the surface of the water, they added to the drag of the towing apparatus, but as in the previous tests, that drag was measured independently and subtracted from the total. The results of the second towing test are shown in Table 5-2 and both towing test results are plotted in Figure 5-3. It is to be noted that the drag of the submarine is reduced at three knots from the value at two and one half knots. Since there is very little experience at M.I.T. in towing underwater bodies, this drag reduction could very well be explained by inaccuracies in the experimental set-up. But the

| Speed KTS | Total Drag lbs | Support Only | Sub Only |
| --- | --- | --- | --- |
| 1.0 | 1.05 | 0.58 | 0.47 |
| 1.5 | 2.31 | 1.26 | 1.05 |
| 2.0 | 3.47 | 2.067 | 1.40 |
| 2.5 | 5.60 | 3.34 | 2.26 |
| 3.0 | 6.28 | 4.31 | 1.97 |

TABLE 5-2

Results of Second Towing Tank Test

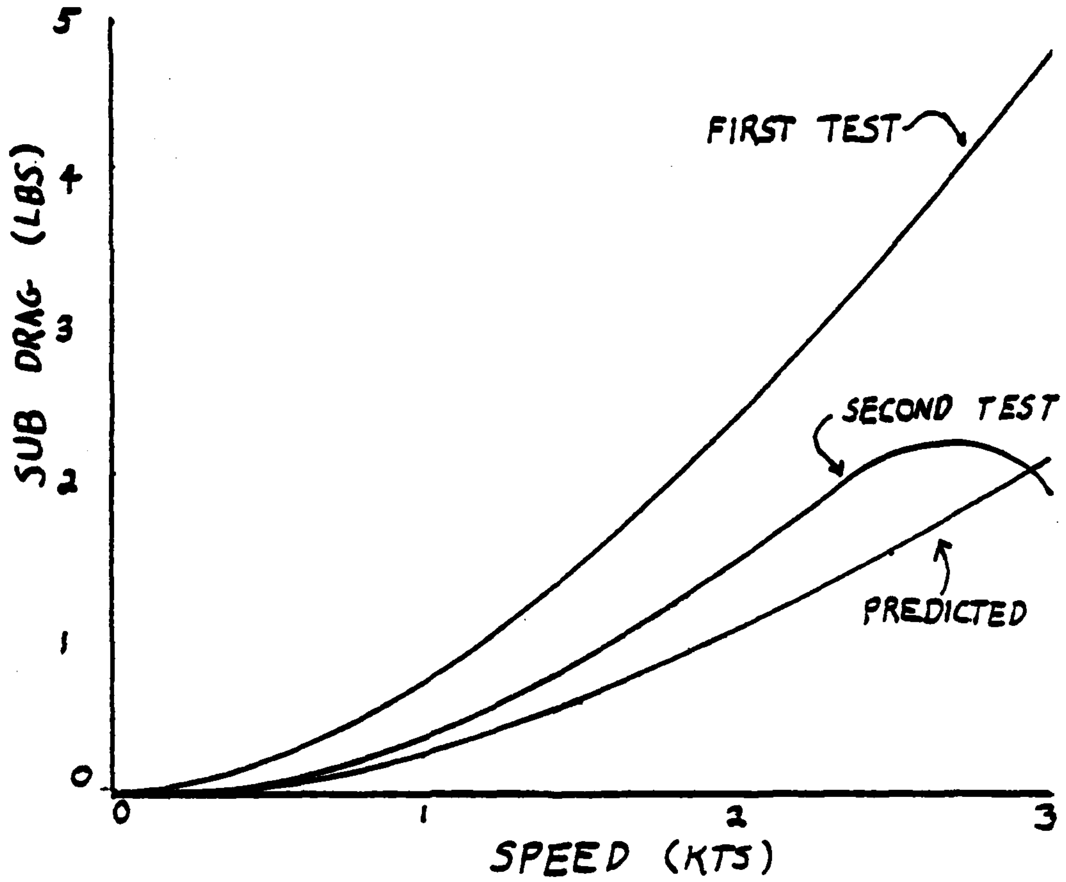



FIGURE 5-3 Speed Resistance

reduction is quite large when compared to an extrapolated value of what the drag at three knots would be on a smooth speed-resistance curve. During the tests, it was observed that the rubber skin was not totally inflated at a speed of two and one-half knots. Whereas at three knots, the skin was nicely inflated and took a very streamlined shape. Since the measured value for resistance at three knots is very nearly that value predicted by both model tests and by calculations, the excessive resistance at lower speeds is assumed to be a result of incomplete inflation of the rubber skin. Thus (if the assumption is correct) the submarine has a "hump" in its speed-resistance curve and the value of drag at the peak of the hump is approximately the value of maximum thrust which the propulsion system was designed for. As the propulsion system degrades, a pronounced reduction in speed may be observed with only a slight reduction in thrust as the submarine becomes unable to "get over the hump".

## 5.3 MOTOR TUBE PRESSURE TEST

The shafts for the control fin servo motors and the propulsion shaft pass through bulkhead seven and into the motor tube. The bulkhead penetrations are made

using rotating lip seals of the Bal-Seal design. These seals are well proven, but there installation and placement is critical to their efficient operation. In order to test the seals, a pressure test of the motor tube was accomplished. The motor tube was removed from the rest of the submarine and a blank bulkhead was machined to take the place of bulkhead number six. The entire motor tube was then enclosed in a pressure vessel and the pressure was increased to 350 psi. The pressure was held for six hours. When the motor tube was removed and inspected, no appreciable leakage was noted.

## 5.4 BALLAST AND TRIM TESTS

Once the vacuum tests and pressure tests were completed, the pressure hull was considered to be watertight. The next step in the testing was to install as much of the actual equipment as possible inside the sub and to add compensating weights at those locations where equipment was not yet ready for installation. The submarine was then floated in a shallow tank and its ballast tanks were filled. Weights were then added to the submarine at appropriate locations until the submarine floated at zero trim and with very slight positive buoyancy. This was to be the final weight and trim of

the submarine in the submerged condition. Next, slightly more weight was added so that the submarine actually submerged to the bottom of the tank. The ballast tanks were then deballasted using the installed ballast system which was activated by the pair of wires which penetrate bulkhead number two. These wires are normally used to arm the emergency ballast dry cells, but also can act as a switching device if normal battery power is not connected as in these tests. The ballast system worked satisfactorily and the submarine came to the surface floating with a slight trim by the stern.

# CHAPTER 6

## RELIABILITY AND MAINTAINABILITY

One of the biggest incentives for the construction of Robot II was that the first generation robot submarine needed constant attention to keep it working. It was not designed to facilitate maintenance and many of its components were selected on the basis of low price rather than reliability. Experience with that submarine has caused the developers of Robot II to approach problems of reliability with more care.

### 6.1 STEPS TAKEN TO IMPROVE RELIABILITY

The design and development of Robot II was accomplished with paramount concern for reliability and maintainability. The design of the pressure hull is such that it can be disassembled easily and in discrete sections so that maintenance can be performed in one area without disturbing the other parts. The o-ring seals between compartments are designed and installed so that they provide maximum sealing efficiency and can be visually inspected without disassembly. Each of the compartments can be separated from the others using only the minimum number of connections. In all cases except

for the ballast and trim compartment, the only connections which need be broken are one or two electrical cable connectors. As much as was possible, piping runs were made external to the pressure hull and were designed to be removed with the framework of the outer skin. This was done to minimize the possibility of leaks within the pressure hull and to reduce the number of connections required for assembly of two adjacent compartments of the hull. The rubber skin itself, although difficult to fabricate and test, was designed solely to facilitate access to the internal components of the submarine. It is intended to be removed and installed easily so that internal adjustments and repairs can be made with minimum effort.

One of the major criteria for the selection of materials for Robot II was that of reliability. The material from which most of the submarine is made is 6061 T6 aluminum alloy. This alloy is considered to be the work horse of aluminum for the marine industry. It is not susceptable to stress corrosion cracking and is resistant to most localized or general types of corrosion except galvanic. It has excellent hardness and strength. (See Appendix II). All the fasteners used on Robot II

are of either aluminum or stainless steel so that no galvanic cells are created. The nose and tail cones were carefully constructed of fiberglass to resist damage from impact or mishandling.

Reliability was also a major consideration during the selection of the individual components within Robot II. For example, the gel cell batteries were selected because they are unlikely to outgas during charging; they do not contain a liquid acid which might spill on other components, and they have a good reputation. The motors used for propulsion and fin control are of the absolute highest quality and were well tested prior to installation. The electrical connectors were chosen because of their high quality and because they can not be connected in a reverse position. The connector can be permanently attached by fastening their bodies together with machine screws thus eliminating any possibility of inadventent loss of electrical continuity. All the piping used in the submarine is made of either aluminum or plastic to minimize corrosion and all the connections are made using highly reliable Swagelok fittings.

Operational problems which might cause the loss of the submarine are always a possibility. Consequently, a fairly large percentage of the trim and ballast compartment is dedicated to the emergency fail-safe system which will automatically deballast the submarine if electrical power is lost. This system is also intended to insure that the submarine will return to the surface if it fails to surface for some other reason since electrical power will surely be lost eventually as the gel-cell batteries are depleted. Thus the only accidents which would cause a total loss of the submarine are flooding beyond the capability of the ballast tubes or submergence to beyond the crush depth of the hull. It is very important, however, that the fail safe system be in good working order; so it should be tested often and its dry cell batteries should be renewed before each extended mission in deep water.

## 6.2 POSSIBLE PROBLEMS

In spite of all the measurestaken to the contrary, there are some circumstances or situations which might cause some problems if the users of the submarine are not aware of them. The dry cell batteries were mentioned in the previous paragraph with regard to the emergency

safeguard they provide. They might, however, if ignored for long periods of time, be a source of trouble within the ballast tube. As with any dry cell battery, the cell will eventually corrode and leak from its casing if not removed for a long time. For that reason the dry cells should be removed from the trim and ballast compartment if the submarine is to be stored for a long period.

Another possible source of trouble is the penetrations into the pressure hull. There are three such penetrations. The small vacuum plug holes, one in bulkhead number two and one in bulkhead number six, are very small and easily overlooked. Yet they will surely cause flooding of the submarine if they are not in place prior to submergences. The third penetration which could easily be a problem is the "watertight" electrical receptacle on bulkhead number two. The receptacle and plug are designed to withstand pressures up to 20,000 psi if the plug is secured in place, but it is not watertight if the plug is removed.

The two toggle valves located at the very top of the submarine's outer framework, were deliberately positioned so that their handles would point upward when they are in the wrong position for operation. Thus the

rubber skin could not be zipped. One of the valves vents the ballast tanks and the other isolates the tanks from the air supply. They must both be in the correct position if the ballast system is to work properly. Both toggles must be down before the submarine submerges.

The battery connections were discussed in paragraph 4.1.1 as well as the possible reversal of battery polarity. But the reversal of battery polarity is potentially the worst possible maintenance related accident and should therefore be reemphasized. The battery support plates have been cemented in place on one end to prevent their being interexchanged and the angle aluminum brackets have also been cemented. But with some effort, the batteries could still be put in backwards. The battery terminals must be on the starboard side.

The feedback potentiometers on the control fin servo motors were selected because they have good physical dimensions and because they are constructed in such a way as to be easily mounted on the servo motor shaft. The original shaft of the potentiometer was removed and a nylon sleeve was installed to provide a friction fit between the shaft and the wiper arm of the potentiometer. One of the

unknown quantities of the submarine is the reliability of these potentiometers since the friction fit of the sleeve might eventually begin to slip or the life of the potentiometers may have been reduced when they were modified.

# APPENDIX I

# CALCULATIONS

## I.1 RESISTANCE CALCULATION

Main propulsion motor selection in the design of Robot II was made based upon the resistance of the vessel at a speed of three knots. The resistance was predicted by model tests described in Reference (1). Since initial towing tests did not closely match the model test results, the resistance is calculated here using standard practice as described in Reference (4) and Reference (5).

The 4165 hull form has the following characteristics:

Wetted surface = $.33094\ L^2$ $\qquad$ $L/D = 7$

$LCB = x/L = .4484$ $\qquad$ $C_p = .6$

Volume = $.9617 \times 10^{-2}\ L^3$

Skin Friction:

$$C_f = \frac{.075}{[\log_{10} NR - 2]^2}$$

$$NR = VL/\nu = \frac{VK\ (1.689)L}{\nu} = 3.002 \times 10^6$$

$C_f = .00374$ $\qquad$ $D_f = 1.69$ lbs

## Base Drag

$$C_{Fb} = C_f \frac{S_{wet}}{S_B}$$

$$+ (.00374) \left[\frac{.33094L^2}{\frac{(3.5)^2}{4}\pi}\right] = 1.02$$

$$C_{DB} = \frac{0.029}{\sqrt{C_{fB}}} = .029 \quad \text{(based upon base area)}$$

$$\text{Base drag} = C_{DB}(.5\rho V^2 S_B) = 0.048 \text{ lbs} = D_B$$

## Form Drag

$$C_r = C_f[1.5 \ (D/L)^{3/2} + 7 \ (D/L)^3]$$

$$C_r = .00042 \qquad D_r = 0.189 \text{ lbs}$$

## Appendages

Wetted surface of fins = 34.4 in$^2$

Typical $C_a$ = 0.006

$$\text{Drag of fins} = C_D(\tfrac{1}{2}\rho V^2 S) = \frac{.006(.5)(64)(25)(34.4)}{(32.2)(144)}$$

$$D_a = .036 \ (4)$$

$$= 0.14 \text{ lbs}$$

Seam Drag

Seam width = 3/8"

Seam area = 3/8 (88.88)(4) = 133.32 in$^2$ = 5.1%

Seam height = .02"

$C_s = 1.2\ C_f$   based on area of protuberances

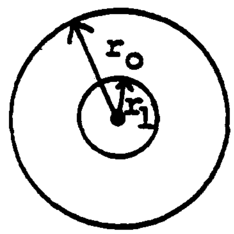
$$D_s = \frac{(1.2)(.00374)(.5)(64)(25)(133.32)}{(32.2)(144)} = 0.10 \text{ lbs}$$

Total drag = $D_f + D_B + D_r + D_a + D_s$ = 2.17 lbs.

## I.2 SHRINK FIT OF THRUST BEARING

One design change which was made very late in the development of Robot II was the addition of a thrust bearing on the main propulsion shaft. The decision was made to attach the thrust collar to the shaft by using a shrink fit. Reference (6) shows the method by which the amount of interference was determined. The basis of that work is reproduced here for convenience:

Since the outside diameter of the collar was to be much larger than the inner, it was first necessary to determine whether to heat or cool the collar in order to expand the inner diameter.




$\Delta r^*$ = radial strain

$\Delta r^o$ = circumferential strain

$$\Delta r^* = -\frac{1}{2}\alpha\Delta T(r_o - r_1), \quad \alpha(\text{stainless steel}) = 9.6 \times 10^{-6}\ {}^oF$$

$$\Delta T(\text{liquid nitrogen}) = -380^oF$$

$$C = 2\pi r \rightarrow r = \frac{C}{2\pi} \rightarrow \Delta r = \frac{\Delta C}{2\pi}$$

$$\Delta C = 2\pi r\alpha\Delta T \rightarrow \Delta r^o = r_1\alpha\Delta T$$

$$\Delta r = \Delta r^* + \Delta r^o = \alpha\Delta T(r_1 - \frac{1}{2}(r_o - r_1))$$

$$\Delta r = \alpha\Delta T(\frac{3}{2}r_1 - \frac{1}{2}r_o)$$

for $\Delta T < 0$, $\Delta r > 0$ if $r_1 < 1/3\ r_o$. Since, in the case of the thrust collar, the outside radius is of the order three times larger than the inner, it was decided to neither heat

nor cool the collar but only to cool the shaft. Using liquid nitrogen the reduction in shaft diameter is:

$$\Delta D = D\alpha\Delta T = 1.37 \times 10^{-3} \text{ in}$$

To determine the stress in the shaft and collar:

$$P = E\frac{\delta}{r_1}\frac{(r_1^2)(r_o^2 - r_1^2)}{2r_1^2(r_o^2 - r_1^2)} = \frac{\delta}{r_1}\frac{(r_o^2 - r_1^2)}{2\, r_o^2}$$

$$E = 28 \times 10^6 \text{ psi}$$

In the shaft, $\sigma_{rs} = \sigma_{\theta s} = -P$

In the ring, $\sigma_{rr} = -P \qquad \sigma_{\theta r} = 1.33P$

$$r_o = .875 \text{ inch}$$

$$r_1 = .375 \text{ inch}$$

The inside radius of the collar was undersized by .0004 inches so that a .001 inch clearance was allowed when the shaft was cooled. Thus

$$\delta = .0004$$

$$P = 25629.2 \text{ psi} = -\sigma r_s = -\sigma_{\theta s} = -\sigma_{rr}$$

$$\sigma_{\theta r} = 34086.83$$

Since the stress in the ring was sufficient to provide a good shink yet but below the yield strength of the metal, .0004 inches was determined to be a good interference dimension.

## I.3 CRUSH DEPTH

A pressure hull thickness of one-fourth inch was selected in Reference (1) to allow for sufficient strength in bending. The question of how deep the submarine could safely go was left unanswered. Reference (4) gives the formula by Windenburg for calculating the critical pressure for shell instability assuming the number of lobes in the failure, $n = \pi D/L$. He asserts that the formula is 99% accurate.

$$P_{cr} = \frac{2.42E}{(1 - \nu^2)^{3/4}} \times \frac{(\frac{t}{D})^{5/2}}{(\frac{L}{D} - .45(\frac{t}{D})^{1/2})}$$

$t = 1/4$ inch

$D = 8.25$ inch

$L = 28.7$ inch

$E = 1 \times 10^7$ psi = Youngs modulus for 6061 aluminum

$\nu = .33$ = Poisson's ratio

$\frac{t}{D} = .0303$

$\frac{L}{D} = 3.4788$

$P_{cr} = \underline{1240.05 \text{ psi}}$

which corresponds to a depth of <u>2755.7 ft</u>.

For simple hoop stress

$$P_{cr} = \frac{\partial t \sigma_y}{D} = 2424.24 \text{ psi} \qquad \sigma_y = 4 \times 10^4 \text{ psi}$$

which corresponds to a depth of 5387.21 ft. so the submarine should be capable of depths up to 2755 ft.

# APPENDIX II

## PROPERTIES OF 6061 T6 ALUMINUM ALLOY

| | | |
|---|---|---|
| Composition | 1.0% | Mg |
| | 0.6% | Si |
| | 0.25% | Cu |
| | 0.25% | Cr |

Density = .098 $lb/in^3$ @ $68^oF$

Youngs Modulus, $E = 10^7$ psi

Yield Strength, $\sigma_y = 40 \times 10^3$ psi

Tensile Strength, $\sigma_{TS} = 45 \times 10^3$ psi

Thermal Expansion $\alpha = 21.8\ \mu_{in}/in^oF$

Specific Heat, $C_p = 0.23$ cal/g

Poisson's Ratio, $\nu = 0.33$

Fatigue Limit = 14000 psi

Heat Treatment

| | Temp $^{o}F$ | Time Hr. | Cooling |
|---|---|---|---|
| complete anneal | 775 | 2-3 | furnace cool to $500^{o}F$ $50^{o}F$/hr max |
| remove cold work | 650 | none | not critical |
| solution heat treat $T_4$ | 960-1010 | 10 min - 1 hr in salt bath, longer in air | cold water quench |
| precipitation T6 | 345-355 | 6-10 | not critical |

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